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How the Cost of Electricity Varies with Laser Efficiency and Target Gain

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The cost of electricity in a laser fusion power plant is relatively insensitive to the efficiency of the laser, if the target gain is approximately 110. The cost of electricity will be more sensitive to laser parameters such as the beam uniformity, the operation and maintenance costs, and the capital costs.

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CONTENTS

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I. INTRODUCTION

In a laser fusion power plant, some fraction of the gross electric power output is recycled back to feed the laser. That recycled fraction is inversely proportional to the product ηG, where η is the efficiency of the laser, and G is the target gain. This has led to the erroneous conclusion that in a laser fusion power plant one should maximize the product ηG, and that this product should be at least 10.

The important economic parameter in a fusion power plant is not the recycled fraction, but rather the cost of electricity (COE) that is put into the power grid. With simple formulas that evaluate the COE, this memo shows that:

1. The COE is a function of the separate values of η and G, *not* just their product.
2. For direct drive laser fusion, with a likely value of G ~110, the COE is nearly independent of η over a wide range of η. There is thus no reason to emphasize the laser's efficiency as compared to other physical parameters that can have a much greater impact on the COE. (Assumes that the laser's capital and operating costs are independent of its efficiency.)
3. A krypton fluoride laser with η=7% has nearly the same COE as a diode pumped solid state laser with an η=10%. (Assumes that the two lasers have the same capital and operating costs for the same output energy.)
4. A higher laser efficiency can sometimes lead to a higher, not a lower, COE.

Many people are skeptical of any calculations of the COE for a fusion power plant, because there are still too many uncertainties in the basic fusion concept, and there are too many costs that can not yet be evaluated with any confidence. However the results in this memo do not depend upon these uncertainties, because the study only utilizes *ratios* of COE; the specific capital and the operating costs drop out of the equations.

II. BASIC FORMULAS

The COE is usually expressed in cents per kilowatt-hour, and can be written:

$$COE = \frac{dC/dt}{f E_n} \tag{1}$$

The parameter dC/dt is the cost per unit time, and includes the costs of building and operating the power plant: its capital cost, fixed charge rates, operation and maintenance, pellet fabrication, availability factor, etc. The parameter f is the repetition rate of the system in pulses per second. The parameter E_n is the net

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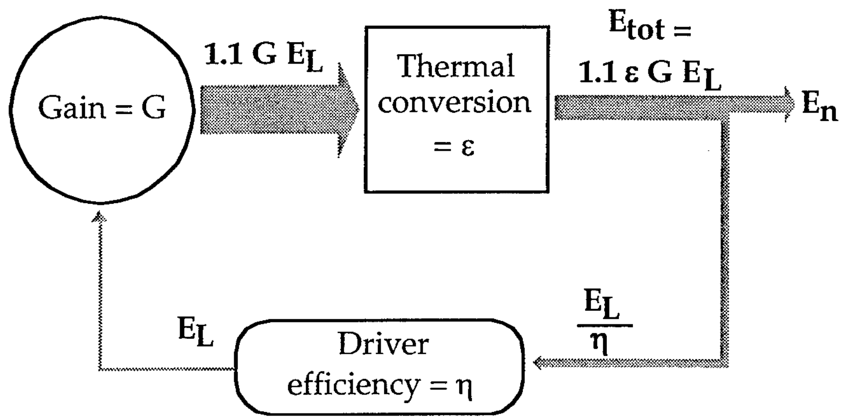
electric energy per shot in Joules delivered to the power grid. The product fE_n is therefore the net power output in Watts. All that has been left out of the above equation is the cost of the plant decommissioning, and some of the auxiliary power requirements. We have written the equation this way because we plan to look at only the *variation* of the COE with respect to the driver efficiency. The costs C are then a constant and drop out of the analysis.

The net electrical energy per shot E_n can be derived from the following graph:



The factor 1.1 is an estimate of the blanket multiplication, based upon the Sombrero fusion power plant study[1]. We easily see that the net electric energy into the grid from each laser shot can be written as:

$$E_n = E_L\left[1.1\varepsilon G - \frac{1}{\eta}\right] \tag{2}$$

Note that E_n is *not* a function of just the product ηG. Thus COE is also not just a function of ηG. We plan to substitute Eq. (2) into (1).

Assumption #1: Fixed gross electric power, fE_{tot}. In many past fusion reactor studies, the net output power fE_n was held constant. Then changes in any one physical parameter, such as the laser efficiency η, required changes in several other physical parameters such as E_L, G, etc. It was then difficult to determine the impact of changing any one physical parameter. Fixing the net power output may be appropriate for fission power plants, and perhaps also for magnetic fusion power plants, but it is clearly inappropriate for laser fusion, where a significant and variable fraction of the power can be recycled. It seems preferable to fix the *gross* power, given by fE_{tot}. Then one can fix the size and cost of the turbines that convert the thermal energy to electrical energy.

Assumption #2: Fixed repetition rate f. In general, to minimize the COE one should maximize the repetition rate. For a fixed laser energy and reactor chamber size, one would always make more money by increasing the repetition rate of the system. No one is yet certain what the maximum chamber clearing rate will be, but we do know we want to maximize it. This memo just assumes that f is that maximized constant. Since we have already fixed the gross electric power, fE_{tot}, we can now also fix the chamber size and its cost, the pellet gain G, the pellet factory costs, and the laser energy E_L.

Assumption #3: Fixed cost *C***.** We have now fixed the repetition rate, the cost of the turbines and heat flow equipment, the size and cost of the reactor chamber, the pellet factory costs, and the laser energy. To fix C we only need to make one additional assumption: that changes in the laser efficiency do not affect the capital cost of the laser. This assumption is clearly wrong in any real system. However for the purpose of this study we want to logically separate out changes in laser cost from changes in laser efficiency. We therefore fix C. It does not matter here whether the laser is 90% of the total capital cost of the facility, or 10% of the total capital cost. We only need to assume that it is a fixed value.

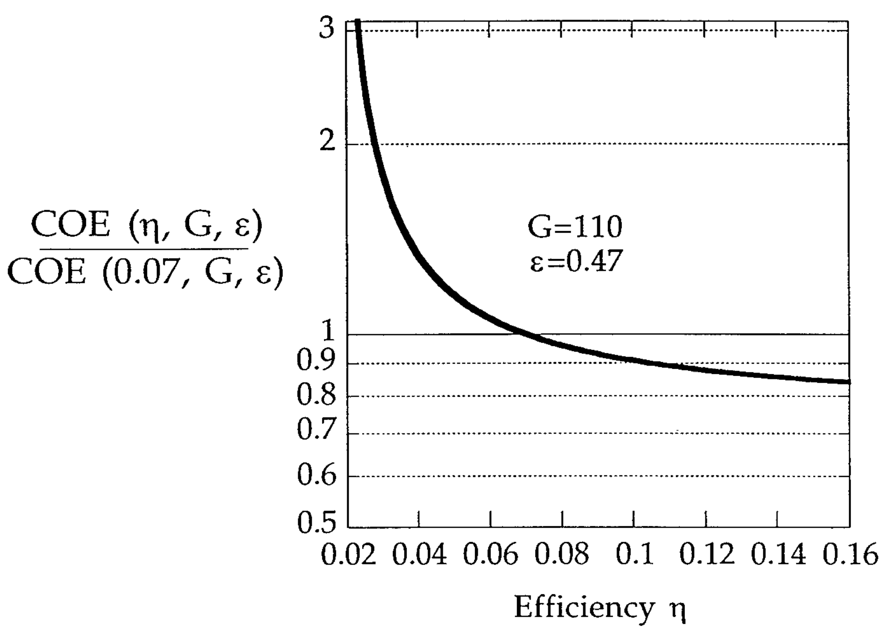
We can now combine Eqns. (1) and (2) to obtain the ratio:

$$\frac{COE(\eta, G, \varepsilon)}{COE(7\%, G, \varepsilon)} = \frac{E_n(7\%, G, \varepsilon)}{E_n(\eta, G, \varepsilon)} = \frac{\left[1.1\varepsilon - \frac{1}{0.07G}\right]}{\left[1.1\varepsilon - \frac{1}{\eta G}\right]} \tag{3}$$

The COE has been normalized to a laser efficiency of 7%, because that is the expected value for a KrF laser in a power plant.

III. VARIATION OF LASER EFFICIENCY

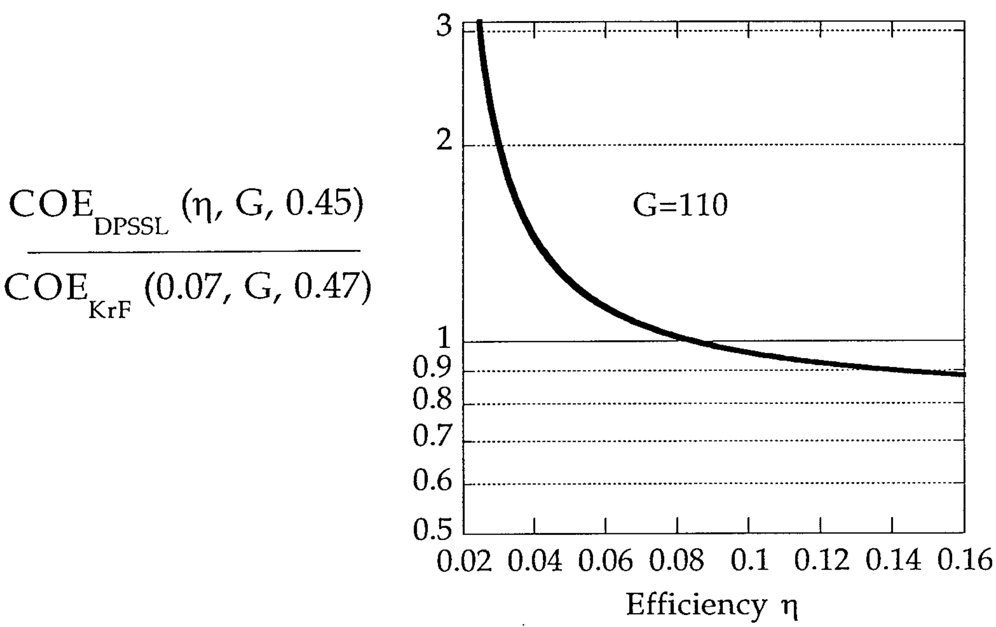
With Eq. (3) one can evaluate how a change in the efficiency of a laser modifies the COE. Note again that the above ratio is a function of both G and ηG, not just ηG. The ratio is plotted below for G=110 [The steam cycle efficiency is chosen to be the same as the value in the Sombrero study, ε = 0.47; this includes re-utilization of the waste heat from the KrF amplifier). We use a semi-log plot, since we are interested in fractional changes of a dimensionless ratio, not in some absolute value of COE.



Note that an increase in the laser efficiency from η=7% to η=10% only reduces the COE by 9%. If the laser efficiency is reduced from η=7% to η=5%, then the COE increases by 15%. In this semi-log plot, with G=110, the curve appears to rise sharply when the efficiency drops below about 5%.

IV. COMPARISON OF KrF and DPSS LASERS

The Sombrero power plant study used a KrF laser. It assumed that the laser gas medium would operate at a temperature of 300 °C, and that the waste heat could be used to preheat the feed water in the steam generator. That raised the net efficiency from ε=45% to ε=47%. Solid state lasers can not operate at an elevated temperature, which would limit the conversion efficiency to ε=45%. The next plot therefore compares the COE of a solid state laser at various efficiencies to the baseline KrF laser with 7% laser efficiency. (It includes the questionable assumptions that the capital costs of the two lasers are the same in dollars per Joule, as are the maintenance costs.)



We see that a DPSSL with 10/7 (=1.43) times the laser efficiency of a KrF laser has only a 4% lower COE. This is clearly insignificant, compared to uncertainties in the capital and operating costs of the two lasers.

V. RELATIONSHIP BETWEEN LASER EFFICIENCY AND CAPITAL/OPERATING COSTS

The previous analysis varied the laser efficiency while keeping constant the capital cost of the laser. One might assume that a higher laser efficiency would lead to a lower capital cost. For example, with a KrF laser, if one could increase the coupling efficiency from the e-beam into the laser gas then one would need fewer power supplies to produce the same laser inversion. Then an increase in the laser efficiency would be accompanied by a decrease in the capital cost.

But sometimes an increased laser efficiency can *increase* the capital cost. For example, there have been proposals to increase the laser efficiency of a DPSSL by increasing the number of diodes and reducing their pulse duration. The lasing medium could then be pumped to the same inversion level but with reduced fluorescence loss. The laser efficiency has been increased, but with the penalty of an increased capital cost for the diodes.

VI. SENSITIVITY OF COE TO VARIOUS PHYSICAL PARAMETERS

The above plots showed that the COE is weakly dependent upon the laser's efficiency, if the efficiency is greater than about 5% and the target gain is about 110. Laser efficiency is of course still worth maximizing, *if all other parameters can be held constant*. Here are some of the other parameters that could have a much greater impact on the COE.

(1) **Sufficient laser bandwidth and focal beam uniformity.** The Nike KrF laser has demonstrated the bandwidth and the beam focal uniformity that is required to implode direct-drive targets. Nd:glass and other solid state lasers do not yet meet those requirements. Some DPSSL laser media have inherently narrow bandwidths. Solutions have been proposed to enhance the bandwidth and beam smoothing of solid state lasers, but they have not yet been verified experimentally. The solutions may or may not be technically feasible. Reduced laser beam uniformity would likely reduce target performance.

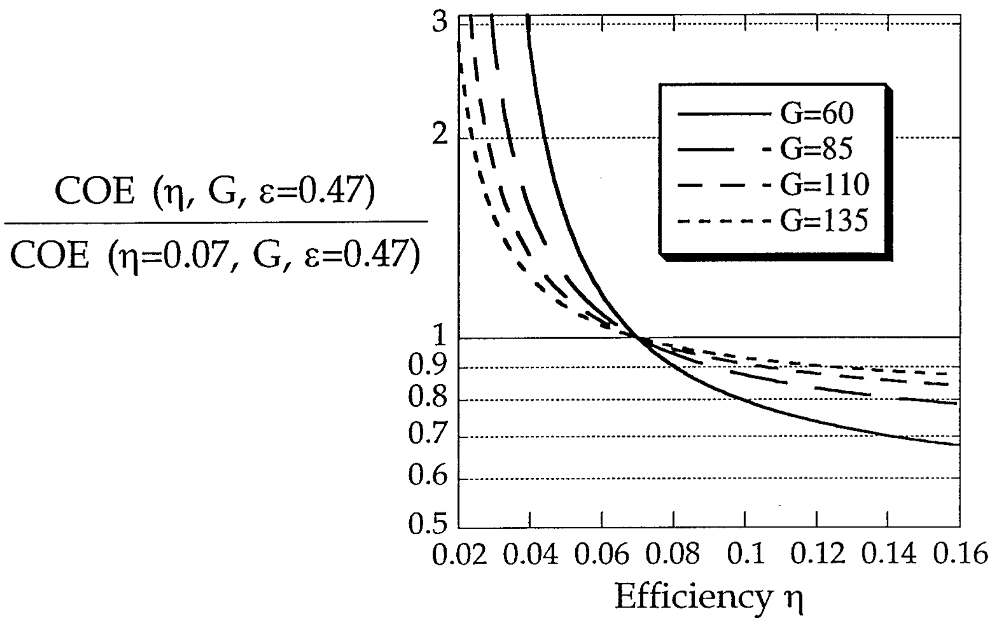
(2) **Sufficiently low laser operation and maintenance costs.** After a few hundred shots, the Nike KrF laser suffers significant damage to the e-beam foils and to the amplifier windows. These components are then replaced. For a power plant, the lifetime needs to be extended to about 10^9 shots between major maintenance. Solutions to the KrF foil and window problems have been proposed, but they may or may not be feasible. If the DPSSL laser crystal is replaced with another crystal that has three times the bandwidth, for better beam uniformity, then it would also require three times the laser intensity for efficiency extraction of the inverted energy. The higher laser intensity may or may not produce significant optics damage.

(3) **Sufficiently low laser capital costs.** Today's diodes cost a few dollars per peak Watt. For an economically attractive COE using a DPSSL, the diode costs must be reduced to about ten cents per peak Watt. This low cost may or may not happen with automated production.

(4) **Sufficient target gain.** The above analysis assumed that the target gain will be 110. This is based upon uncertain computer code predictions and a limited laser-target data base[2]. If the target gain is significantly less than 110, then there would be less gross yield. A greater fraction of the power would have to be recycled back to the laser, and there would then be a greater advantage to a higher laser efficiency.

VII. COE VARIATION WITH TARGET GAIN

The following graph shows the variation of the COE ratio to laser efficiency, for various target gains G. For lower values of G, the curves are steeper, and there would be a greater advantage to a higher laser efficiency. Remember however that these are just ratios. As G decreases, there would be less energy available to sell into the power grid, even with a very efficient laser, and the absolute value of the COE would eventually reach unacceptable values.



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[1] I. V. Sviatoslavsky et al, Fusion Tech. **21**, 1470 (1992)
[2] S. Bodner et al, Phys. Plasmas **5**, 1901 (1998)